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Towards a Table-Top Laser Driven XUV/X-Ray Source

Kramer Akli
OHIO STATE UNIVERSITY THE

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Final Report

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Laser-driven relativistic electron beams were investigated experimentally and via 3D large-scale plasma simulations. These fast electrons mediate the transfer of energy from the laser to other absorption channels and drive many applications, including bright x-ray and Extreme ultraviolet radiation (EUV or XUV) sources. The investigation was carried out in two phases. In the first phase, reduced mass targets were irradiated with intense ultra-short laser pulses. Bright monochromatic x-rays and broadband XUV emissions were achieved by optimizing the electrostatic sheath fields surrounding the target. Electron recirculation in the plasma was identified as a mechanism of emission enhancement. The study also revealed that this laser-driven source of radiation has a small source size, short duration, and high photon fluxes suitable for point projection radiography and for probing matter under extreme environments. In the second phase, laser-irradiated micro-engineered Si micro-wire arrays were investigated. An order of magnitude enhancement in the total number of electrons with energy higher than 10 MeV was experimentally demonstrated. The study revealed that these advanced micro-engineered targets not only enhance the total number of electrons and their kinetic energies but also behave as a

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FINAL PERFORMANCE REPORT FOR AWARD NO.FA9550-12-1-0341

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ABSTRACT

Laser-driven relativistic electron beams were investigated experimentally and via 3D large-scale plasma simulations. These fast electrons mediate the transfer of energy from the laser to other absorption channels and drive many applications, including bright x-ray and Extreme ultraviolet radiation (EUV or XUV) sources. The investigation was carried out in two phases. In the first phase, reduced mass targets were irradiated with intense ultra-short laser pulses. Bright monochromatic x-rays and broadband XUV emissions were achieved by optimizing the electrostatic sheath fields surrounding the target. Electron recirculation in the plasma was identified as a mechanism of emission enhancement. The study also revealed that this laser-driven source of radiation has a small source size, short duration, and high photon fluxes suitable for point projection radiography and for probing matter under extreme environments. In the second phase, laser-irradiated micro-engineered Si micro-wire arrays were investigated. An order of magnitude enhancement in the total number of electrons with energy higher than 10 MeV was experimentally demonstrated. The study revealed that these advanced micro-engineered targets not only enhance the total number of electrons and their kinetic energies but also behave as an electromagnetic lens that guides and collimates the electron beam.

INVESTIGATION OF X-RAYS AND EXTREME ULTRAVIOLET RADIATION WITH REDUCED MASS TARGETS (RMT):

Goals of the project

The main objective of this first phase of the project is to use reduced mass targets of various dimensions and geometries to generate hot and dense plasmas in the laboratory conditions. Of special interest is the investigation of target geometry that maximizes plasma radiation in the x-ray and extreme ultraviolet spectral range. The end goal is to achieve a versatile laser-driven radiation source with a small source size, short duration, and high photon fluxes.

Approach

It is a well-known fact that hot dense plasmas are bright emitters of radiations as evidenced in nature by the sun, stars, and gamma ray bursters. In laboratory conditions, bright x-ray sources are routinely produced with high-power lasers. However, due to their large size and low repetition rate, laser-based radiation sources use is limited. In this project, we study the feasibility of using a fairly compact high-repetition rate laser to create a bright radiation emitter in the form of a "miniature star" in the laboratory. Our approach relies on heating an initially solid density target to temperatures in the range of 100,000 to 1,000,000 degrees Kelvin. Our simulations predict that fast electrons, generated by an ultra short-pulse laser, will heat up the target to high temperatures via electron "recirculation" or "refluxing". To briefly summarize how the mechanism works: hot electrons generated from the laser-plasma interaction near the critical surface are sent into the solid target. If the vast majority of hot electrons have a range that is greater than the target thickness, a fraction of these electrons leave the target region. This causes a large space charge to build up on the target at the edges, and only the most energetic electrons (with energies exceeding the space charge potential) can leave. Most electrons are attracted back to the target, losing energy to the background electrons and ions each time they traverse the target. **Figure 1** shows the longitudinal and transverse electrostatic sheath fields induced when an ultra-short

pulse laser interacts with RMT. The inset shows select electron trajectories in these sheath fields.

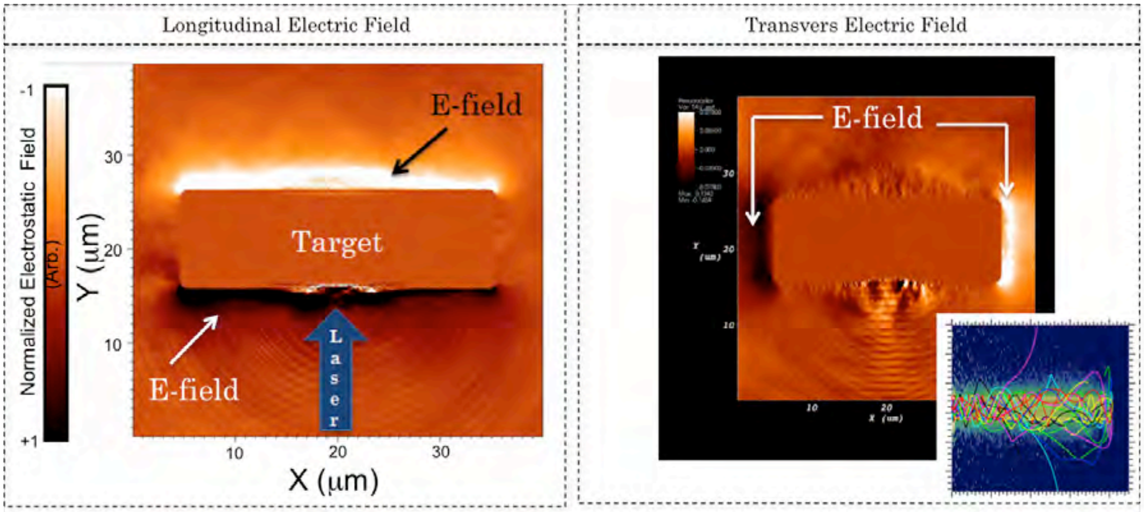


Figure 1: Plasma induced electrostatic sheath fields and electron trajectories affected by refluxing

Experimental setup

We conducted a systematic study of laser-driven radiation sources using the Scarlet laser at The Ohio State University. The laser delivered 9J of energy in 150fs pulses, reaching peak intensity of ~ 10^{20}W/cm^2. A suite of diagnostics was used to characterize the laser-produced plasma, induced radiation, and charged particle emission. These include an extreme ultraviolet imager operating at 68 eV photon energy, K-shell emission imager operating at 8 keV, two x-ray spectrometers based on highly ordered pyrolytic graphite crystals (HOPG). **Figure 2** shows a typical data from these instruments. The rear and front HOPG x-ray spectrometers allow us to compare monochromatic Cu characteristic emission in the forward and backward directions. The Cu imager provides information on electron spatial distribution. The XUV imager provides Planckian emission patterns.

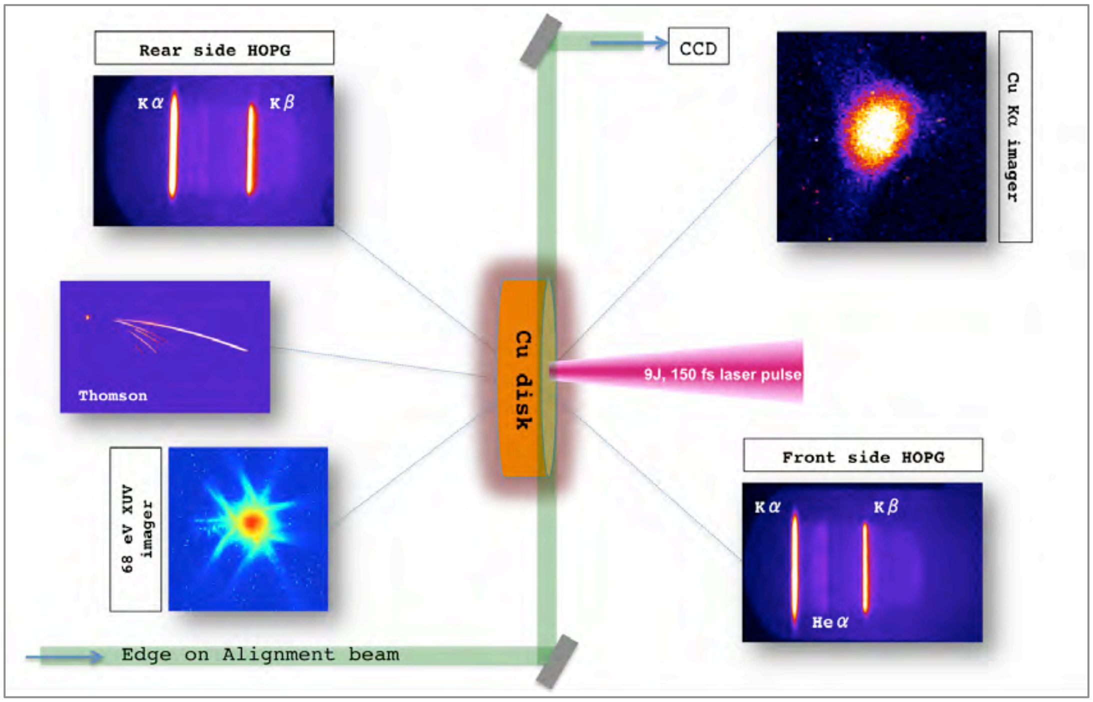


Figure 2: Typical data from a short pulse interacting with a Cu target

<u>Accomplishments/New Findings</u>

Effect of target transverse dimensions: To study the effects of the transverse dimension of the target on laser-produced plasmas, we have used Al/Cu/Al disks with variable diameters: 500 µm, 350 µm, and 100µm. These targets were irradiated at the best achievable focus with our F/2.2 off-axis parabola. Cu Kα images are shown in **Figure 3**. For the large targets (500µm diameter), we distinguish two emission regions: a central region with strong emission surrounded by low emission zone. This indicates the presence of gradients in K-shell source. As, the diameter of the target is reduced (350 µm); the central spot region increases while the low emission zone decreases. The presence of an intermediate emission zone indicates that electron refluxing is not optimal. However, the emission gradients decrease with decreasing target diameter. Reducing the target diameter to 100 µm resulted in more uniform emission zone, suggesting that the electrostatic sheath fields surrounding the small disk trap more electrons, yielding efficient refluxing.

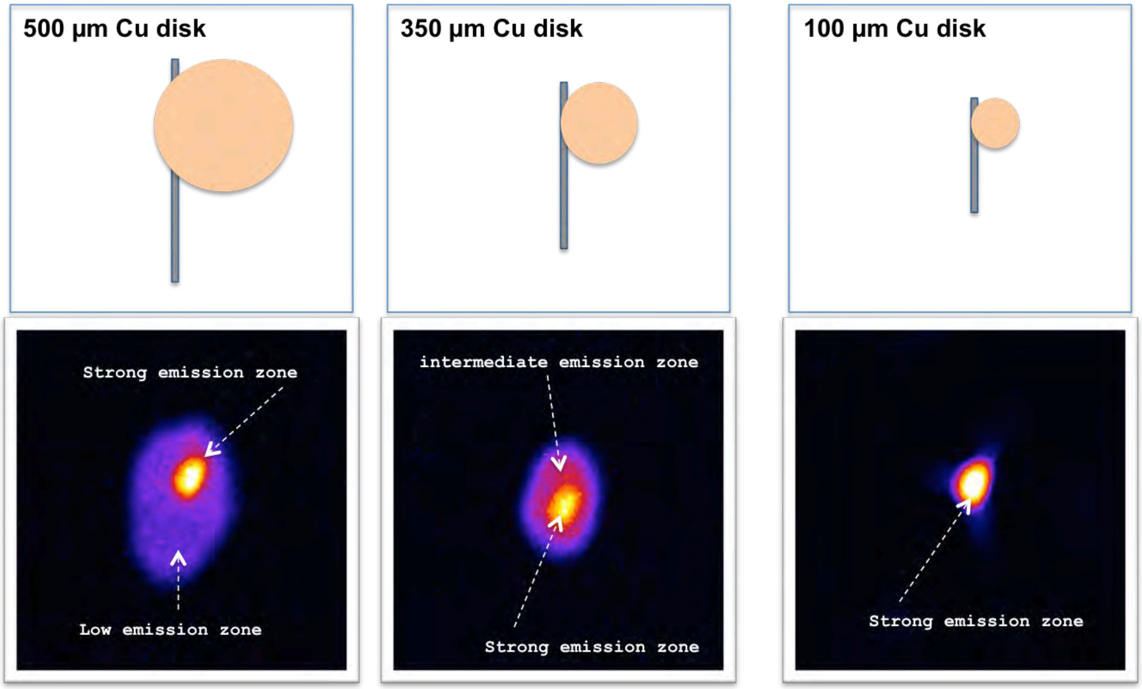
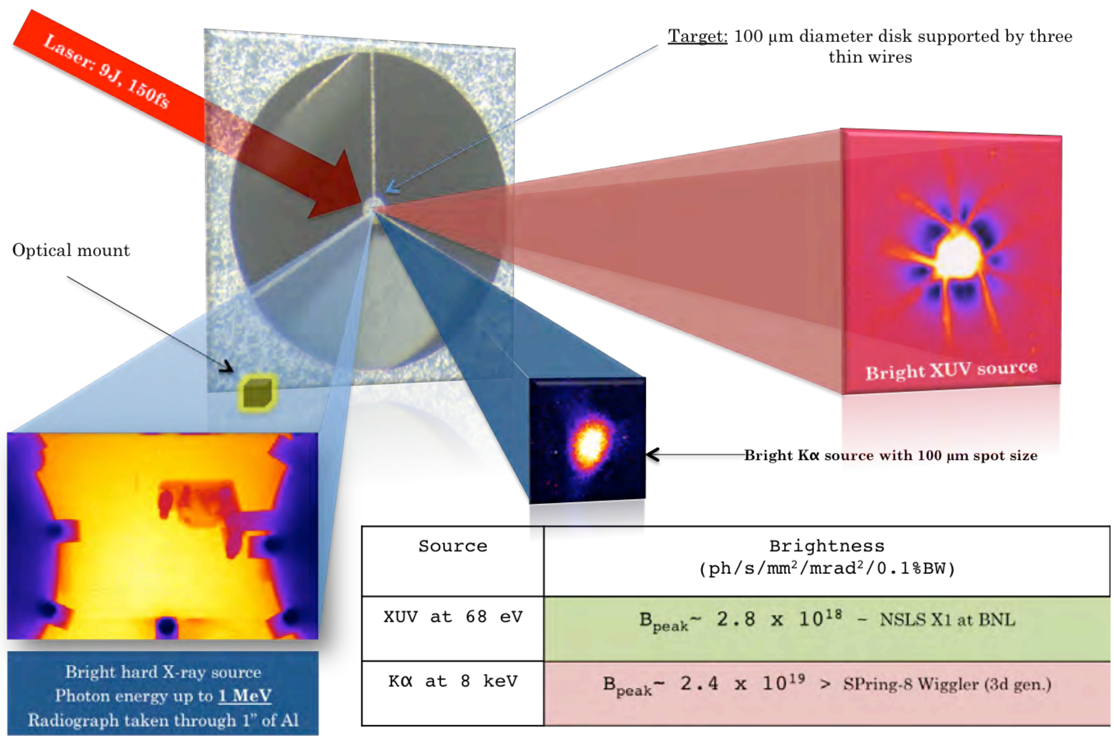


Figure 3: Effect of target diameter on the uniformity of monochromatic Cu Kα emission

Effect of target longitudinal dimensions: We focused on investigating the effect of varying the target thickness on plasma radiation by keeping the target diameter fixed at 100 μm. Three thicknesses of Cu were used: 1 μm, 3 μm, and 6 μm. In each case, the Cu tracer layer was coated with 1 μm Al on the front surface and 1 μm Al at the rear surface to minimize hydrodynamic expansion and direct laser interaction with Cu. We observed a correlation between electron refluxing and target heating. For the thickest target (6 μm), the K-shell and XUV maps show that the entire target is heated up by electron refluxing. However, the region of uniform heating is smaller than that of the thinnest target (1 μm). This indicates that the longitudinal dimension of the target adversely affects the heating uniformity. The best way to achieve uniform high-temperature plasma is to keep the thickness of the Cu layer less than 3 μm and the transverse dimension at 100 μm or less. **Figure 4** shows a summary of data obtained in a single laser shot with a 3 μm thick 100 μm diameter disk. The peak XUV brightness was determined to be ~ $2\text{x}10^{18}$ ph/s/mm^2/mrad^2/0.1% BW. This is equivalent to the brightness of NSLS X1 beamline at BNL and this source could potentially used for

material science research and lithography. The monochromatic K-shell emission, from the same shot, had a peak brightness of ~ 2.4×10^{19} ph/s/mm^2/mrad^2/0.1% BW (equivalent to Spring-8 wiggler brightness). A bright hard X-ray radiation (up to 1MeV photon energy) was also achieved and used to radiograph objects through one inch thick Al. Furthermore, the radiation source size is less than 100 µm which makes this versatile source ideal for a point projection radiography and Thomson scattering characterization of matter under extreme environments.



Source	Brightness (ph/s/mm^2/mrad^2/0.1%BW)
XUV at 68 eV	$B_{peak}\sim 2.8\times10^{18}$ – NSLS X1 at BNL
Kα at 8 keV	$B_{peak}\sim 2.4\times10^{19}$ > SPring-8 Wiggler (3d gen.)

Figure 4: All in one laser-driven radiation source: the interaction yielded 80 eV temperature hot dense plasma. The radiation source characteristics are: 1) less than 100 µm source size. 2) 1.5×10^{12} photons per pulse at 8 keV. 3) 2.8×10^{13} photons per pulse at 68 eV. 4) Intense Bremsstrahlung emission with photon energy as high as 1 MeV.

Relativistic electron beam enhancement & guiding with silicon micro-wire arrays

Goals of the project

The objective of the second phase of the project is to use structured interfaces to enhance and control laser-driven electrons.

Approach

Many exotic phenomena have been predicted and experimentally observed in laser solid-matter interactions in the relativistic regime. These include the production of relativistic electrons, the acceleration of protons and heavy ions, the synthesis of attosecond pulses from plasma-induced harmonics, and the creation of electron-positron jets. The investigation of these processes has been focused on exploring their dependence on various laser pulses as well as target parameters (spatial dimensions, density, and atomic number). More recently, another target degree of freedom is being introduced to enhance laser matter interactions. Structured interfaces including nanoparticles, snowflakes, and nanowires have been reported to enhance laser absorption and proton acceleration. *Our approach relies on using periodic highly ordered Si micro-wires to enhance and guide laser-driven electron beams.*

Target fabrication

Our collaborators at California Institute of Technology undertook the Si micro-wire arrays fabrication. The overall process can is describe by the flow chart in ***Figure 5***. Si wafer were used as a growth substrate. Si {111} is commonly used to grow vertical tower structures. In this project, we also used the inclined structures where wires are uniformly tilted 20° off normal. These targets were fabricated using a Si {211} substrate. The surface of the substrate is oxidized so that there is a layer of SiO_2 that is a few hundred nm thick. Then a thin layer of photoresist is applied using spin coating. Creating circular holes on the photoresist layer using photolithography sets the position and diameter of the wires (the wires will end up growing in these holes). Using a buffered HF

etching, the uncovered SiO_2 under the holes is removed so that pure Si is exposed inside the holes. The holes are then filled up with a few hundred nm of Cu via thermal evaporation onto the photoresist, followed by liftoff to dispose of the photoresist layer. The substrate is then annealed and Si wires are grown at the location of the Cu balls through vapor-liquid- solid growth while other portion of the surface is still protected by the SiO2 layer. The simple mechanism for vapor-liquid-solid growth is shown in Figure 6. Introducing a gas flow of SiCl4 and H2, the wire growth is carried out. The Cu balls work as a metal catalyst. They are melted during the growth, forming a solution of $SiCl_4$. Once the solution is supersaturated, the Si substrate acts as a seed crystal and the Si in the solution starts to crystallize on it. The Cl^- ions are bound to hydrogen, forming HCl gas.

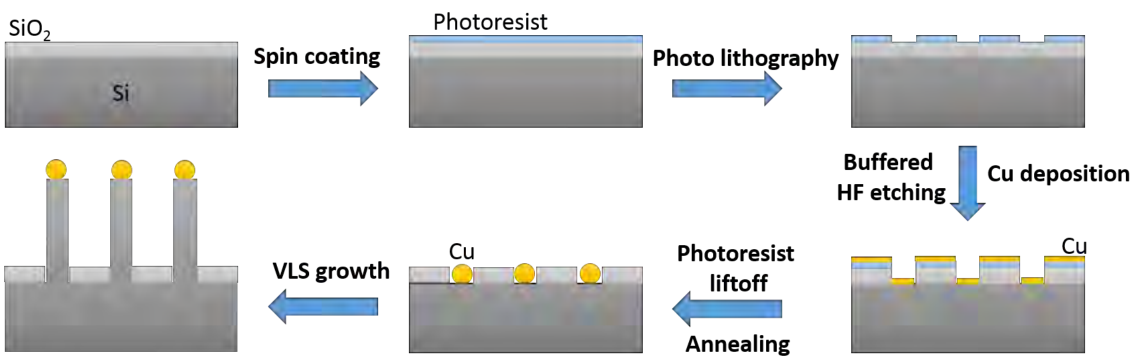


Figure 5: Flow chart describing overall process of Si micro-wire arrays fabrication

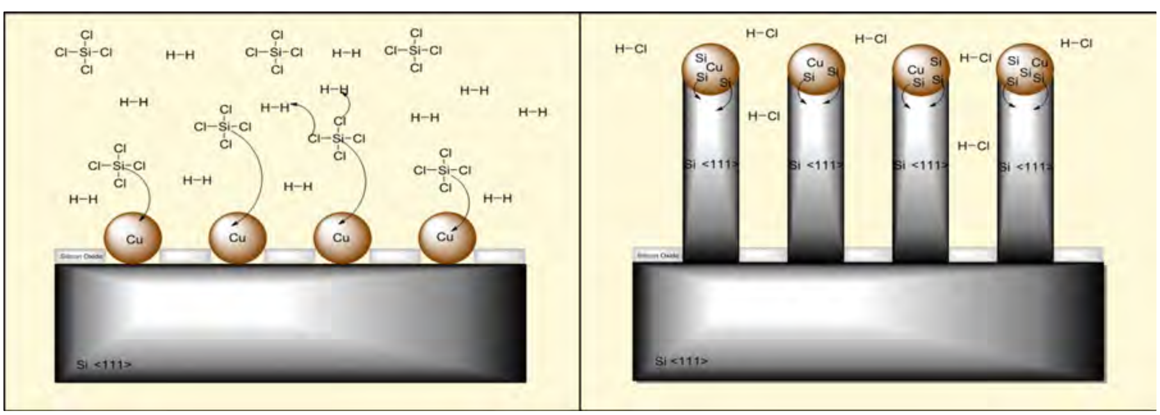


Figure 6: Mechanism for growing Si towers using vapor-liquid-solid technique with Cu catalyst

Four types of targets were fabricated and used in the experiment: the 700 µm thick target with vertical structures, the 400 µm - 450 µm thick target with inclined structures. The SEM images of the structured targets are shown in ***Figure 7***.

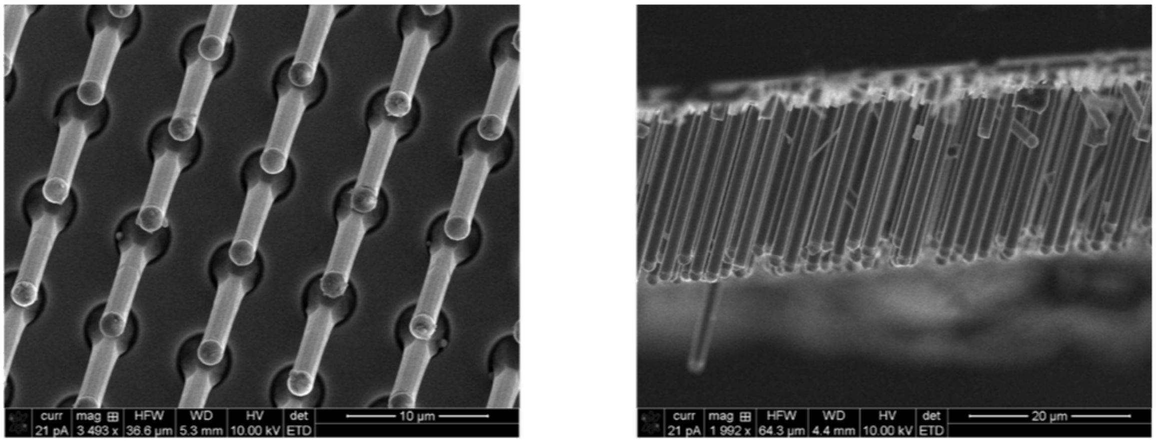


Figure 7: A scanning electron microscope (SEM) images of Si micro-wire targets: a, top view showing wire spatial distribution. b, side view showing the orientation of the wires with respect to the 450 µm thick at Si substrate.

<u>**Accomplishments/New Findings**</u>

Acceleration and guiding mechanism identification: The mechanism of light interaction with micro-wire arrays is investigated with the particle-in-cell (PIC) code VLPL in three-dimensional geometry. A high-contrast laser pulse with an intensity $\sim 10^{21}$ Wcm^{-2} is normally incident on a structured interface. The target consists of highly aligned periodic carbon wires 20 µm long, 1.5 µm thick attached to a 5.6 µm thick aluminum substrate. Snapshots of the interaction and electron beam energy distributions from simulations are shown in Fig.8. As the pulse enters the micro-wire array (Fig.8a), electrons are pulled out of the wires by the laser field. These electron bunches are periodic and they are separated by one laser wavelength on the same wire. The electron bunches on two opposite wires are separated by a half laser wavelength reflecting the oscillatory nature of the driving laser field. The laser pulse has a phase velocity approximately equal to the speed of light as it propagates between the wires (Fig.8b). Consequently, electrons

pulled from the surface of the wires are injected into the laser pulse and accelerated via direct laser acceleration mechanism (DLA). Finally, when the laser beam reaches the flat interface, electrons originating from the wires have acquired significant kinetic energy. They propagate in the forward direction and escape the target as indicated by the green periodic bunches at the rear side of the target (Fig.8c).

It is worth noting that lower energy electrons are produced as well when the pulse irradiates the flat surface holding the wires. The most energetic electrons are the ones that originated from the wires and experienced acceleration via DLA. Fig.8d shows the electron energy distribution for the micro-wire array target. As a baseline comparison, we have carried out simulations of a flat interface without the wires using the same laser and simulation parameters. It is clear from these results that the performance of micro-engineered targets is superior to that of a flat target in producing and accelerating electrons. In the micro-wire array target, electrons with energies as high as 90 MeV are produced compared to 20 MeV maximum electron energies in flat targets. An exponential fit to the electron energy distribution from the micro-wire array target yields kT_e = 16 MeV, much higher than the ponderomotive scaling at the same intensity (kT_e = 7 MeV). The total number of relativistic electrons with energies higher than 1 MeV is enhanced by a factor of 25 with the structured interface compared to flat targets. The electron beam from the Si array carries a charge of 8 nC. We also observe that the accelerated electrons travel forward in the vicinity of the wires. This suggests the presence of a guiding mechanism induced by laser plasma interactions. We examined the electric and magnetic fields in the neighborhood of the wires. Fig.8e (left) shows a vector plot of the electric field surrounding one representative wire. The electric field is radially oriented and points away from the wire. This is consistent with fields induced by a distribution of positive charge. In our case, this field is induced by charge separation as the electrons are pulled from the wires by the laser, leaving the ions behind.

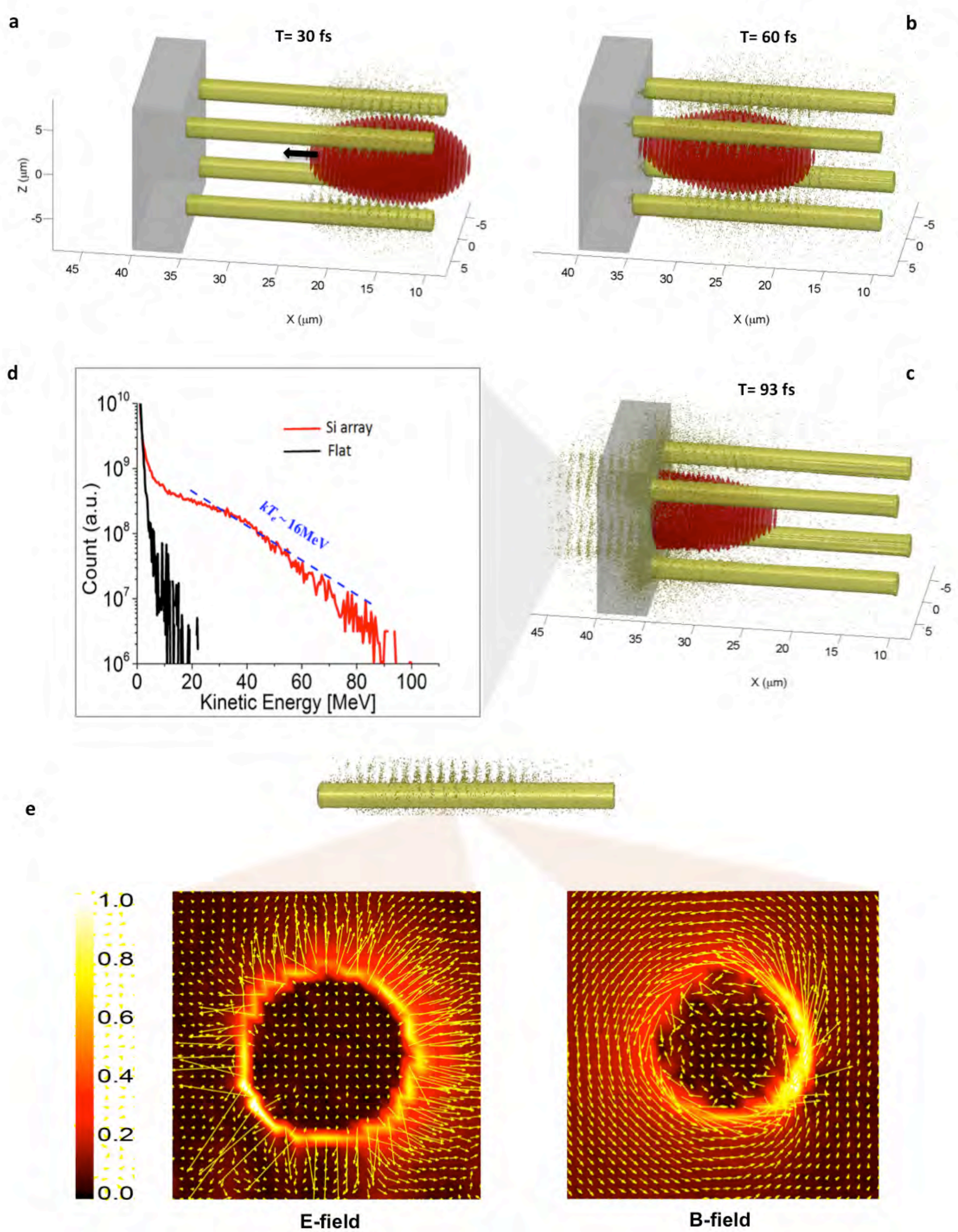


Figure 8: Three-dimensional PIC simulations of an intense short-pulse laser interacting with micro-wire arrays: Laser pulse ($I = 10^{21}$ $Wcm^{-}2$) is polarized in the y direction and propagates along the x direction from right to left. The target consists of highly aligned periodic carbon wires 20 μm long, 1.2 μm thick attached to 5.6 μm thick aluminum substrate. a, b, and c are snapshots of the interaction at t=30 fs, t= 60 fs, and t=93 fs respectively. d, electron beam energy distributions from micro-wire array (red) and at Al target (black). e, electric and magnetic fields around the wire, average dover the wire length.

Fig.8e (right) shows the magnetic field in the vicinity of the wire. The orientation of the magnetic field and field line configuration are consistent with the magnetic field of the current carrying wire. The magnetic field is induced by the return currents in the wire as the plasma responds to electric current unbalance produced by the forward going super-thermal electrons. These plasma-produced electric and magnetic fields provide a guiding mechanism for electrons that are accelerated by DLA. The electric field induced by charge separation tends to attract electrons toward the wires. The magnetic field tends to push them away, toward the laser axis. Electrons with velocities such that the transverse electric and magnetic forces cancel one another are guided in the forward direction. The simulation results suggest that these advanced targets can be used as micro-photonic devices to manipulate the laser matter interaction on small scales and subsequently control the production of secondary particle beams.

Proof-of-principle experiment: a proof-of-principle experiment was conducted on the Scarlet laser facility at The Ohio state University. To manipulate the laser-matter interactions, we used Si micro-wire arrays as targets. The ability of three-dimensional, vertically aligned Si structures to enhance light absorption relative to planar c-Si absorbers has been demonstrated in the context of solar cells. Silicon wires with 1.5 µm diameter, 15-25 µm length, and 7 µm spacing were grown on a 450 µm thick flat Si substrates using vapor-liquid-solid (VLS) growth method (***Figure 7***). The laser delivered 4-5 J of energy on target with the main pulse to amplified spontaneous emission (ASE) intensity contrast better than 10^{10}. The 40 fs duration laser pulse was focused with an F/2.2 off-axis parabola to a 3 µm full width at half maximum focal spot, reaching a peak intensity $1\text{x}10^{21}$ W $\text{cm}^{-}2$. To prevent laser back-reflections from damaging the front-end optics, the wires were grown at 22.5 degrees with respect to the flat substrate normal. The laser propagation direction was parallel to the wires and electrons escaping the rear side of the target were collected with a magnetic spectrometer coupled to imaging plate detectors. The magnetic field in the center of the gap of our spectrometer is about 0.6 T and the instrument collected electrons at 30 degrees from the laser axis. The experimental results are summarized in Fig.9. Electron beam energy distributions from

Si micro-wire arrays are shown in red and the distributions from flat targets are shown in black. The electron beam energy distributions recorded with flat targets are similar. In both Fig.9a and Fig.9b, the cut-off energy for the electron beam is around 30 MeV, close to the 20 MeV predicted by our simulations. A significant enhancement in total number of electrons and their mean energy is obtained with Si micro-wire arrays. Two independent shots were taken with similar structured targets, yielding cut-off energies of 70 MeV (Fig.9a) and 60 MeV (Fig.9b). For both structured targets, two electron populations characterize the spectra: a low energy population in the range of 0.5-20 MeV and a high electron energy population that extends to 60-70 MeV range. This suggests, as seen in the simulations, that the spectrum is a combination of electrons from the bulk of the target and electrons from the wires that were accelerated by DLA. An exponential fit to the data gives kT_e = 18 MeV, and kT_e = 11 MeV for data in Fig.9a and Fig.9b respectively. This is consistent with the predictions of our 3D PIC simulations of kT_e = 16 MeV.

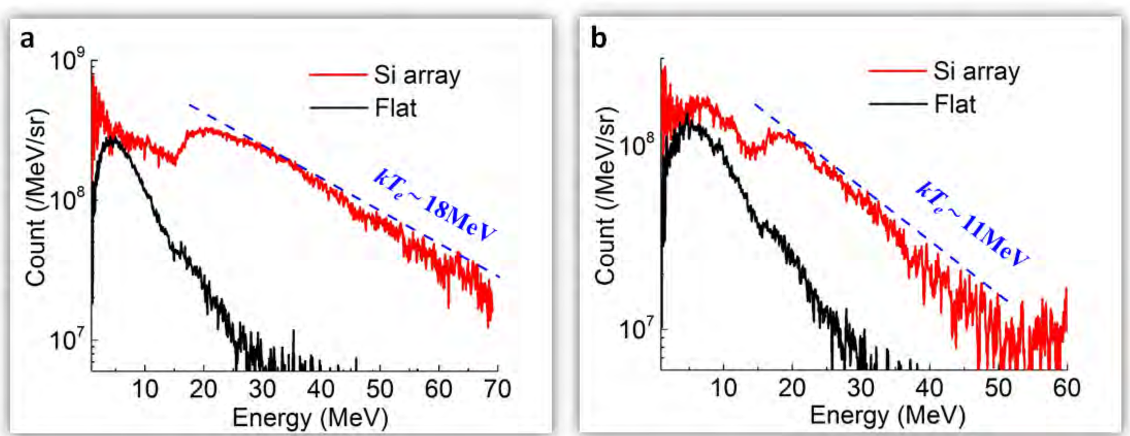


Figure 9: Experimental results: Escaping electrons energy distributions for 4 laser shots. . Flat target spectra (black), Si arrays spectra (red). a, Si array target-1 and baseline flat substrate. b, Si array target-2 and baseline flat substrate

PERSONNEL SUPPORTED BY THE YIP GRANT

- Kramer U. Akli – Principal Investigator
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- Matthew McMahoon- Graduate student (partial support)
- Robert Mitchell- Graduate student (partial support)
- David Andereck- Senior personnel (partial support)
- Jordan Kotick- Undergraduate student (partial support)
- Kevin George- Graduate student (partial support)

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“Laser Driven Electron and X-ray Sources Based on Micro-structured Targets”

By Sheng Jiang

The Ohio State University

Advisor: Prof. Kramer U. Akli

(2015)

“Laser-Driven Ion Acceleration from Novel Target Designs”

By Jordan Kotick

The Ohio State University

Advisor: Prof. Kramer U. Akli

(Pending)

HONORS AND AWARDS

Sheng Jiang:

- Student poster award first prize, FIW International Workshop, Oxford, UK

Jordan Kotick:

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- Autumn Semester of 2015 scholarship, Undergraduate Honors, College of Engineering at OSU.

YIP SPONSORED PUBLICATIONS

1. *L. L. Ji, A. Pukhov, I. Yu. Kostyukov, B. F. Shen, and K. Akli;*
"Radiation-Reaction Trapping of Electrons in Extreme Laser Fields"
Phys. Rev. Lett. 112, 145003 (2014) *DOI: 10.1103/PhysRevLett.112.145003*

2. *L. L. Ji, A. Pukhov, E. N. Nerush, I. Yu. Kostyukov, B. F. Shen, and K. U. Akli; "Energy partition, gamma ray emission, and radiation reaction in the near-quantum electrodynamics regime of laser-plasma interaction"*
Phys. Plasmas 21, 023109 (2014) *DOI: 10.1063/1.4866014*

3. *S. Jiang, A. G. Krygier, D. W. Schumacher, K. U. Akli, and R. R. Freeman*
"Effects of front-surface target structures on properties of relativistic laser-plasma electrons",
Physical Review E 89, 013106 (2014).

4. *S. Jiang, A. G. Krygier, D. W. Schumacher, K. U. Akli, and R. R. Freeman "*Enhancing Bremsstrahlung Production From Ultraintense Laser Solid Interactions With Front Surface Structures*",*
Eur. Phys. J. D. (2014) 68:283 *DOI:10.1140/epjd/e2014-50339-4*

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1. *"Leveraging nano-science to manipulate light-matter interactions at relativistic intensities", international conference on high energy density physics, August 23-27, 2015; San Deigo, California.*

2. *"Increasing High Energy Electron Yield Using Front Surface Target Structures", NIF and JLF User Group Meeting, February 8-11, 2015; Livermore, California.*

3. *"Enhancing Bremsstrahlung Radiation using Front Surface Target Structures", The 56th Annual Meeting of the Division of Plasma Physics (DPP), October 27-30, 2014; New Orleans, Louisiana.*

4. *"Enhancing Resistive Guiding of Hot Electrons Using Front-Surface Target Structures", 13th International Workshop on Fast Ignition of Fusion Targets, September 14-18, 2014; Oxford, England.*

5. *"Shaping the Spectrum of Hot Electrons using Structured Targets", The 55th Annual Meeting of the Division of Plasma Physics (DPP), November 11-15, 2013; Denver, Colorado.*

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Organization / Institution name

The Ohio State University

Grant/Contract Title
The full title of the funded effort.

Toward A Tabletop Laser-driven XUV/X-ray Source

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0341

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Kramer U. Akli

Program Manager
The AFOSR Program Manager currently assigned to the award

Enrique Parra

Reporting Period Start Date

06/15/2012

Reporting Period End Date

06/14/2015

Abstract

Laser-driven relativistic electron beams were investigated experimentally and via 3D large-scale plasma simulations. These fast electrons mediate the transfer of energy from the laser to other absorption channels and drive many applications, including bright x-ray and Extreme ultraviolet radiation (EUV or XUV) sources. The investigation was carried out in two phases. In the first phase, reduced mass targets were irradiated with intense ultra-short laser pulses. Bright monochromatic x-rays and broadband XUV emissions were achieved by optimizing the electrostatic sheath fields surrounding the target. Electron recirculation in the plasma was identified as a mechanism of emission enhancement. The study also revealed that this laser-driven source of radiation has a small source size, short duration, and high photon fluxes suitable for point projection radiography and for probing matter under extreme environments. In the second phase, laser-irradiated micro-engineered Si micro-wire arrays were investigated. An order of magnitude enhancement in the total number of electrons with energy higher than 10 MeV was experimentally demonstrated. The study revealed that these advanced micro-engineered targets not only enhance the total number of electrons and their kinetic energies but also behave as an electromagnetic lens that guides and collimates the electron beam.

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Archival Publications (published) during reporting period:

1. L. L. Ji, A. Pukhov, I. Yu. Kostyukov, B. F. Shen, and K. Akli;
"Radiation-Reaction Trapping of Electrons in Extreme Laser Fields"
Phys. Rev. Lett. 112, 145003 (2014) DOI: 10.1103/PhysRevLett.112.145003

2. L. L. Ji, A. Pukhov, E. N. Nerush, I. Yu. Kostyukov, B. F. Shen, and K. U. Akli; "Energy partition, gamma ray emission, and radiation reaction in the near-quantum electrodynamics regime of laser-plasma interaction"
Phys. Plasmas 21, 023109 (2014) DOI: 10.1063/1.4866014

3. S. Jiang, A. G. Krygier, D. W. Schumacher, K. U. Akli, and R. R. Freeman
“Effects of front-surface target structures on properties of relativistic laser-plasma electrons”,
Physical Review E 89, 013106 (2014).

4. S. Jiang, A. G. Krygier, D. W. Schumacher, K. U. Akli, and R. R. Freeman “Enhancing Bremsstrahlung Production From Ultraintense Laser Solid Interactions With Front Surface Structures”,
Eur. Phys. J. D. (2014) 68:283 DOI:10.1140/epjd/e2014-50339-4

5. S. Jiang, L. L. Ji , H. Audesirk , N. S. Lewis, A. Krygier, D. W. Schumacher, A. Pukhov, R. R. Freeman, and K. U. Akli “Enhancing and guiding relativistic electrons with Si micro-wire arrays”,
Under preparation (to be submitted to Phys. Rev. Lett.)

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

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Appendix Documents

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